Errors Observed during ACAS Monitoring and Sufficiency of Corresponding Tests in the TCAS MOPS

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Summary

As described in reference (1), a prototype ACAS monitor is being used for data collection and analysis of ACAS transmissions in German airspace. A number of errors were noted in the ACAS transmissions, and questions have been raised about whether current TCAS MOPS tests in these areas are sufficient.

This paper lists each of the observed errors, gives the corresponding tests (if any) from the TCAS MOPS that would have been expected to detect the errors, and offers suggestions for resolution of the error and/or improvement in the tests, as necessary. The paper also notes the potential safety impact of the errors.

The paper concludes that of the ten types of errors observed:

- One error is caused by a difference in a format definition between the TCAS MOPS and ACAS SARPs.
- Eight of the errors, if persistent, should have been detected by existing MOPS tests. Many of the observed errors, however, appear to be intermittent, and therefore, MOPS tests would not be reliable in detecting the errors. Suggestions are given to resolve the errors. Note – suggested wording changes are proposed for two MOPS tests to better detect one of the errors.
- One of the errors does not appear to be completely covered by its existing MOPS test; an additional test is proposed.

References:

(1) "Detected Deficiencies in ACAS RA related transmissions," P.Form, J. Gottstein, R. Mallwitz, Aeronautical Surveillance Panel (ASP), WP ASP 01-12, 27 October 2006
(2) RTCA/DO-185A, "Minimum Operational Performance Standards for TCAS II Airborne Equipment," Dec. 1997, Volume I

1. Introduction

1.1 Purpose of Paper

As described in reference (1), a prototype ACAS monitor is being used for data collection and analysis of ACAS transmissions in German airspace. A number of errors were noted in the ACAS transmissions, and questions have been raised about whether current TCAS MOPS tests in these areas are sufficient.

This paper lists each of the observed errors, gives the corresponding tests (if any) from the TCAS MOPS that would have been expected to detect the errors, and offers suggestions for resolution of the error and/or improvement in the tests, as necessary.

The tests listed are from DO-185A, Volume I, sections 2.4.2.2.3 through 2.4.2.2.5. These tests are described as "end-to-end system tests that verify both the operation of the TCAS/transponder system with external elements, e.g., Mode S grounds sensors and other TCAS aircraft, and also the operation of TCAS with its associated Mode S transponder. The tests verify proper implementation of formats and protocols" in Volume I of the TCAS MOPS.

1.2 Summary of Errors from Reference Paper

The reference paper reports ten different types of observed errors occurring in four different ACAS transmissions. The transmissions and their respective errors can be summarized as follows:

a. RA Broadcast Interrogation Message
   (1) AID field (Mode A Identity code) – unexpected ordering of bits
   (2) AID field (Mode A Identity code) – non-zero X-bit
   (3) ARA field (Active RA) – non-zero bits in area reserved for ACAS III
   (4) CAC (Mode C Altitude code) – entire field equal to zero
   (5) CAC (Mode C Altitude code) – M-bit set to indicate metric units
   (6) AP field (Address/Parity) – broadcast address not equal to FFFFFF

b. TCAS Resolution Message
   (7) CVC, VRC, VSB fields (Cancel Vertical RA Complement, Vertical RA Complement, Vertical Sense Bits) – parity code in VSB not matched to bits in CVC and VRC fields
   (8) MID field (Mode S address) – incorrect address of sender TCAS aircraft

c. TCAS Broadcast Interrogation Message
   (9) AP field (Address/Parity field) – broadcast address not equal to FFFFFF

d. RA Report to Mode S ground sensors
   (10) Suspicious high reply rate

1.3 Safety Impact of Observed Errors

The transmissions in items a and d above are used for monitoring purposes, and errors in these messages are not a safety concern (unless they are used by ground controllers).

Errors in the transmissions in item c (TCAS Broadcast Interrogation Messages), if persistent in duration and widespread across aircraft, could adversely affect the TCAS interference limiting process. TCAS Broadcast Interrogation Messages are transmitted by a TCAS unit once per 8-10 seconds. They include the Mode S address of the transmitting TCAS aircraft and allow each TCAS unit to determine the number of other TCAS units (NTA) in the surrounding area. Errors, such as c(9), that cause this broadcast message to be rejected by surrounding aircraft would result in lower NTA counts and less interference limiting applied than required. This could adversely affect the operation of ground sensors. Note that intermittent errors would not cause problems.

The most serious concern is raised by the observed errors in item b above. TCAS Resolution Messages are used in the TCAS air-to-air coordination process. Persistent errors of the kind listed in b(7) and b(8) above would totally prevent coordination from taking place. Intruder intent information received with a parity code error would be ignored by the receiving TCAS. A coordination message with an invalid sender address would be stored but never used. Both cases could result in two TCAS aircraft performing completely independent maneuvers.

If the errors are of short duration (1-2 scans), then the situation is not as serious. If the coordination process takes place correctly on the first scan and a problem occurs later, then perhaps (if the sense of the RA does not change during the encounter) there would be no consequence. If the problem occurs in the first one or two scans, then the coordination process is delayed. This can result in unnecessary reversals seen by the pilot, among other things.

Monitoring should be continued to understand the extent of errors occurring in the TCAS Resolution Messages. If possible, errors should be traced to the TCAS manufacturer and the manufacturer notified.

1.4 Relevance of U.S. Monitoring to These Errors

The transmissions in a, b, and c above (RA Broadcast Interrogation Message, TCAS Resolution Message, and TCAS Broadcast Interrogation Message) are 1030 MHz (uplink) transmissions transmitted by the TCAS unit. All three are defined as UF=16 interrogations, i.e., long special (air-to-air) surveillance interrogations. They are distinguished from one another by the UDS (U Definition Subfield):

Transmission	UDS Subfield
RA Broadcast Interrogation Message	49_{10}

TCAS Resolution Message	48_{10}
TCAS Broadcast Interrogation Message	50_{10}

The bulk of TCAS-related monitoring done in the U.S., including all monitoring done by Lincoln Laboratory, is restricted to 1090 MHz (downlink) transmissions, so errors in the 1030 MHz transmissions would not be routinely observed in the U.S.

The transmissions in d above (RA Reports) are 1090 MHz transmissions transmitted by the transponder and are routinely monitored in the U.S. The U.S. observations in this case are similar to the observations in Germany.

2. Detection of Errors by TCAS MOPS Tests

2.1 General Comment

With the exception of error a(1), most of the errors observed appeared to occur intermittently and thus would not likely be caught during MOPS testing. Suggestions for dealing with intermittent errors are given below.

During previous monitoring of the Boston airspace, occasional incorrect bits were noted in fields downlinked from aircraft transponders. For Mode S equipped aircraft, the tail number of the aircraft was used to determine the manufacturer(s) of the onboard transponder and TCAS unit. When a particular manufacturer's equipment seemed to exhibit an error frequently, the manufacturer was contacted. The manufacturer generally then ran detailed bench tests of the equipment. Often an error was discovered in the real-time software operation; e.g., a software routine that was assembling an output message field could be interrupted during the assembly process, resulting in errors in the message field. It is possible that something similar is causing the errors observed in Germany.

In addition, during the Boston monitoring, if a particular aircraft exhibited an error constantly, then the tail number of the aircraft was sent to FAA Certification Office with a description of the problem. The Certification Office could contact the aircraft owner and ask that the installation be checked.

In one specific case, every aircraft belonging to one non-US carrier exhibited an 'on-the-ground' vertical status setting when airborne in the Boston area. Lincoln contacted that country's SICASP representative, who then contacted the airline. An installation problem was found in all aircraft of a particular type. After the installation was corrected, the airline provided Lincoln with a schedule showing each aircraft 's flights through the Boston airspace, so that we could verify a correct vertical status setting of 'airborne.'

2.2 RA Broadcast Interrogation Message

Correct formatting and transmission of the RA Broadcast Interrogation Message is tested by "Transmission of RA Report to Mode S Sensor and RA Broadcast Interrogation to Other Ground Receivers," DO-185A, Vol. I, section 2.4.2.2.4.1, Scenarios A and B. All six of the errors observed in this message [section 1.2 above, item a] would be expected to be detected by the MOPS tests, if the errors were persistent, as opposed to intermittent. Specific errors are addressed below. Errors marked with an arrow indicate that a change in requirements and/or tests is needed or recommended.

Error a(1)

⇒ Error a(1), "AID field (Mode A Identity code) – unexpected ordering of bits," is unique in that the error is caused by a difference in the format definition given in the MOPS and SARPs. According to the ACAS SARPs (Volume IV, paragraph 4.3.8.4.2.3.4.5), the 13 bits of the intruder Mode A code are supposed to be ordered in the AID field as C1 A1 C2 A2 C4 A4 0 B1 D1 B2 D2 B4 D4. The TCAS MOPS (Volume I, section 2.2.3.9.3.2.4c) gives the bit ordering as A4 A2 A1 B4 B2 B1 0 C4 C2 C1 D4 D2 D1. The TCAS equipment flying has been designed and tested to the MOPS, so the AID field will not be as defined in the SARPs.

Error a(2)

Error a(2) is listed above as "AID field (Mode A Identity code) – non-zero X-bit." According to both the ACAS SARPs and the TCAS MOPS, the middle bit of the 13-bit AID field (bit 7 or the 'X-Bit') must be set to 0. Various instances were observed in which this bit was set to 1.

Discussion: The AID field contains the Mode A code of own TCAS aircraft. This code is entered by the pilot via the TCAS/transponder control panel into the Mode S transponder, then sent from the transponder to the TCAS unit via the ARINC 429 bus. The Mode A code is sent as 12 bits on the ARINC 429 bus, so it is the responsibility of the TCAS unit to insert the X-bit=0 into the AID field.

All processing relating to this error, from input of the Mode A code to the transponder to transmission of the broadcast by the TCAS unit, is tested by the TCAS MOPS bench tests described in section 2.2 above.

Error a(3)

RA Broadcast Interrogation Messages were observed in which the last seven bits (48-54) of the ARA (Active RA) field were not all equal to zero. These bits are reserved for ACAS III (SARPs) or, equivalently, TCAS IV (MOPS) and currently are required to be zero.

Discussion: The TCAS unit is responsible for filling in the seven reserved bits of the ARA field with zeros. This portion of the TCAS code is tested by the TCAS MOPS bench tests described in section 2.2 above.

Error a(4)

RA Broadcast Interrogation Messages were observed in which the entire CAC field (Mode C Altitude Code) was equal to zero. This is the own aircraft altitude, which is input to the transponder and sent from the transponder to the TCAS unit via the ARINC 429 bus. The TCAS unit is responsible for reformatting the altitude data into the 13-bit CAC field. The entire process (input of the altitude to the transponder, sending to TCAS via the ARINC 429 bus, reformatting by TCAS, and transmission of the broadcast by the TCAS unit) is tested by the TCAS MOPS bench tests described in section 2.2 above. In addition, correct reception of own altitude by TCAS from the transponder is checked in tests "Sense Selection and Communication," DO-185A, Vol. I, section 2.4.2.2.4.2.1, Scenarios A through H.

Error a(5)

RA Broadcast Interrogation Messages were observed in which the 'M-bit' or metric bit was set to 1 in the CAC field (Mode C Altitude Code). As in error a(4) above, the CAC field contains own aircraft altitude, which is input to the transponder and sent from the transponder to the TCAS unit via the ARINC 429 bus. The TCAS unit is responsible for reformatting the altitude data into the 13-bit CAC field, including setting the middle bit (M-bit) to zero. This portion of the TCAS code is tested by the TCAS MOPS bench tests described in section 2.2 above.

Error a(6)

RA Broadcast Interrogation Messages were observed in which the AP field (Address/Parity) field was not equal to $FFFFFF_{16}$. The TCAS unit is responsible for correctly inserting the broadcast address into the outgoing transmission. This portion of the TCAS code is tested by the TCAS MOPS bench tests described in section 2.2 above.

⇨ However, it is recommended that the "Expected Output" sections of the two tests be changed to more clearly state that the broadcast address ($FFFFFF_{16}$) is required in the UF=16, UDS=49 transmissions by own TCAS. Suggested wording changes are given in Attachment A to this paper.

2.3 TCAS Resolution Message

Correct formatting and transmission of the TCAS Resolution Message is tested by "Sense Selection and Communication," DO-185A, Vol. I, section 2.4.2.2.4.2.1, Scenarios A through H. The two errors observed in this message [section 1.2 above, item b] would be

expected to be detected by the MOPS tests, if the errors were persistent, as opposed to intermittent. No suggestions for improvement are given.

Error b(7)

TCAS Resolution Messages were observed in which the four vertical sense bits sent by a TCAS-equipped intruder during the TCAS-TCAS coordination process were not consistent with the parity coding field used to protect the four vertical sense bits. That is, the CVC (Cancel Vertical Resolution Advisory Complement) and VRC (Vertical Resolution Advisory Complement) fields were not consistent with the VSB (Vertical Sense Bits) field. This would cause the receiving TCAS aircraft to ignore the contents of the message, essentially negating the coordination process on that scan.

As stated above, there are eight tests in the TCAS MOPS that check the correct operation of the CVC, VRC, and VSB fields in the TCAS Resolution Message.

Error b(8)

TCAS Resolution Messages were observed in which the MID (Mode S Address) field was not correct. The MID field contains the address of the transmitting TCAS aircraft. It is used by the receiving TCAS during the coordination process to store received vertical intent information into the proper intruder threat file. An incorrect address would cause the intent information to be stored improperly, thereby causing the receiving TCAS to ignore the contents of the message, thus negating the coordination process on that scan.

As stated above, there are eight tests in the TCAS MOPS that check correct operation of the MID field in the TCAS Resolution Message.

2.4 TCAS Broadcast Interrogation Message

Error c(9)

TCAS Broadcast Interrogation Messages were observed in which the AP (Address/Parity) field was not equal to $FFFFFF_{16}$. This would cause the messages to not be received by other surrounding TCAS units.

⇒ The TCAS MOPS currently contains test 2.4.2.1.10.2, “Use of Directional Antenna for TCAS Broadcast Interrogations.” However, this test focuses on aspects of the directional antenna, rather than correct content of the message. An additional proposed test is given in Attachment B to this paper.

2.5 RA Report to Mode S Ground Sensors

RA Reports were observed that persisted for a longer time than expected (longer than 3 minutes in the example sited). Note that this can occur occasionally for legitimate reasons, e.g., formation flights or long approaches to parallel runways. In the Boston monitoring data, there are examples of downlinked RA Reports that range from a few scans to ones that occasionally persist for the entire time the aircraft is in the sensor coverage area – up to 45 minutes or so. Most often the extended duration is due to a stuck bit, most often the RAT (RA Terminated) bit.

Other errors are seen in RA Reports in the Boston area, primarily invalid intruder altitudes in the TIDA field (Threat Identity Data Altitude).

Correct formatting, transmission, and clearing of bits in the RA Report are tested by "Transmission of RA Report to Mode S Sensor and RA Broadcast Interrogation to Other Ground Receivers," DO-185A, Vol. I, section 2.4.2.2.4.1, Scenarios A and B. Generally, in the U.S., errors in the downlinked RA Reports have been traced to errors in the TCAS or transponder real-time software operation, as described in section 2.1 above. The equipment successfully passed the MOPs tests but still could exhibit intermittent problems, requiring detailed investigation by the manufacturer(s).

No improvements in the TCAS MOPS tests are suggested for the RA Report.

3. Summary

Of the ten types of errors observed:

One error is caused by a difference in a format definition between the TCAS MOPS and ACAS SARPs.

Eight of the errors, if persistent, should have been detected by existing MOPS tests. Many of the observed errors, however, appear to be intermittent, and therefore, MOPS tests would not be reliable in detecting the errors. Suggestions are given to resolve the errors. In addition, wording changes are proposed to two MOPS tests to better detect one of the errors.

One of the errors does not appear to be completely covered by its existing MOPS test; an additional test is proposed.

Monitoring should be continued. In particular, monitoring should be continued to understand the extent of errors occurring in TCAS Resolution Messages. These messages are involved in the TCAS air-to-air coordination process, and errors in these messages can have a safety impact.

Attachment A.

Proposed Changes to DO-185A, Volume I, section 2.4.2.2.4.1, "Transmission of RA Report to Mode S Sensor and RA Broadcast Interrogation to Other Ground Receivers," Scenarios A and B.

In Scenario A, under "Expected Output," *When testing with an RTCA/DO-185A compatible Mode S transponder:*

Change the two instances of UF=16, UDS=49 to read:

"UF=16, in MU: UDS=49, ARA=11100010000000, RAC=0000, RAT=0, MTE=0, AID=1010010011100, CAC=0011000101010, AP address* = $FFFFFF_{16}$ at T= 31, 39, 47, 55, 63"

and

"UF=16, in MU: UDS=49, ARA=11100010000000, RAC=0000, RAT=1, MTE=0, AID=1010010011100, CAC=0011000101010, AP address* = $FFFFFF_{16}$ at T= 66"

In Scenario B, under "Expected Output," *When testing with an RTCA/DO-185A compatible Mode S transponder:*

Change the two instances of UF=16, UDS=49 to read:

"UF=16, in MU: UDS=49, ARA=11000010000000, RAC=1000, RAT=0, MTE=0, AID=0101110110000, CAC=1001000101010, AP address* = $FFFFFF_{16}$ at T= 30, 38, 46, 54, 62"

and

"UF=16, in MU: UDS=49, ARA=11000010000000, RAC=1000, RAT=1, MTE=0, AID=0101110110000, CAC=1001000101010, AP address* = $FFFFFF_{16}$ at T= 65"

* i.e., address before parity overlay added and after parity overlay removed

Attachment B

Proposed Changes to DO-185A, Volume I.

Add the following new material at the end of the existing section 2.4.2.1.7.4.2:

"2.4.2.1.7.4.3 Correct Content of Transmitted TCAS Broadcast Interrogation Messages (2.2.3.9.3.2.4 b and 2.2.3.10.2.4))

This test verifies that the TCAS unit under test transmits correctly coded TCAS Broadcast Interrogation Messages for the entire period that the TCAS unit is powered on.

Conditions:

TCAS initialized and operating.

Expected Output:

Msgs: UF=16, with UD1 (bits 33-36) =3, UDS2 (bits 37-40) =2,
MID (bits 65-88) = 24-bit address of own aircraft Mode S transponder,
AP address* = $FFFFFF_{16}$

* i.e., address before parity overlay added and after parity overlay removed

The UF=16 messages are transmitted such that, for any other TCAS II aircraft within 30 nmi. and at any azimuth, the nominal rate of own TCAS Broadcast Interrogation Messages arriving at that TCAS II is 1 per 8 to 10 seconds.

Note: Use of directional antenna for TCAS Broadcast Interrogation Messages is tested in section 2.4.2.1.10.2."

Modify Table 2-69, "Cross-Reference of Requirements to Associated Tests" as follows:

Insert the following line after the line starting 2.4.2.1.7.4.2:

"2.4.2.1.7.4.3	Correct Content of Transmitted TCAS Broadcast Interrogation Messages	2.2.3.10.2.4	TCAS Broadcast Interrogations

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Modify Table 2-70, "Cross-Reference of Associated Tests to Requirements" as follows:

Insert the following line after the line starting 2.2.3.10.2.4:

"	2.4.2.1.7.4.3	Correct Content of Transmitted TCAS Broadcast Interrogation Messages"